# An Investigation of Turbulent Heat Exchange in the Subtropics

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## LONG-TERM GOALS

The long-term goal is to improve our understanding of heat and moisture exchange in the tropics through direct estimates of the fluxes and their related mean variables. The flux of heat across the coupled boundary layers is primarily accomplished by small-scale processes that are parameterized in numerical models. The ultimate goal is to improve the Navy's predictive capabilities in the tropics through an improved understanding of the processes driving the Madden-Julian Oscillation (MJO).

## OBJECTIVES

An objective of the LASP program is to improve our understanding of heat and moisture exchange in the tropics through direct estimates of the fluxes and their related mean variables. The flux of heat across the coupled boundary layers is primarily accomplished by small-scale processes that are parameterized in numerical models. The primary objectives of this research are to:

- Deploy a suite of unique observational assets in and over the Indian Ocean to investigate the MJO.
- Use these measurements to improve the surface flux parameterization for latent and sensible heat used in Navy models and LASP-related observational process studies.
- Quantify the role of air-sea exchange in the formation and propagation of the active phase of the MJO.

We are collaborating with researchers from NCAR, NOAA/ETL, Oregon State University, and other institution to investigate the relationship between boundary layer structure and surface forcing during an MJO event. This is being accomplished through measurements collected from a research vessel that conducted surveys during three 20-40 cruises to investigate air-sea interaction during periods when conditions are favorable for MJO formation (Madden and Julian, 1994). The measurement will include surface meteorological and atmospheric vertical structure and collaboration with numerical modelers and other observational components of the program. **The principle hypothesis of this research is that improved observations and parameterizations of latent and sensible heat fluxes, which is a primary source of energy for these convective systems, will improve our ability to simulate and predict the MJO.**

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## APPROACH

***Flux Measurements:*** The PI (Edson) deployed a Direct Covariance Flux System (DCFS) aboard the R/V Revelle alongside a suite of instruments to measure the short and longwave radiative fluxes, wind speed and direction, temperature, pressure, humidity, and precipitation. The DCFS (Edson et al., 1998) has been used in a number of field programs and would provide estimates of the momentum, sensible heat and latent heat fluxes during ship-based surveys. The PI deployed a newly developed LI-COR LI-7200 infrared gas analyzer that is expected to improve the latent heat flux estimates. This new unit ran alongside the LI-7500 that has been successfully deployed in previous investigations.

The DCFS and infrared hygrometers allow the PI and his colleagues to investigate the exchange of sensible and latent heat between the atmosphere and ocean using the direct covariance method. This method correlates fluctuations in the vertical velocity, $w'$, with fluctuations in the sensible heat, $\rho_a c_p T'$, and latent heat, $\rho_a L_v q'$, per unit volume:

$$Q_H = \rho_a c_p \overline{w'T'} \tag{1}$$

$$Q_E = \rho_a L_v \overline{w'q'} \tag{2}$$

where $\rho_a$ is the density of air, $c_p$ is the specific heat of air, $L_v$ is the latent heat of vaporization, $T'$ and $q'$ are temperature and specific humidity fluctuations, respectively; and the overbar denotes a time average ranging between 10-30 minutes for turbulent fluxes. The sensors are capable of accurately measuring fluctuation at approximately 2 Hz to capture the total flux near the air-sea interface.

Unfortunately, this direct method is generally difficult to implement over the ocean due to platform motion, flow distortion and sensor limitations. Instead, oceanographers and meteorologists often rely on bulk formula such as the COARE 3.0 algorithm (Fairall et al., 1996; 2003) that relates the fluxes to more easily measured averaged wind speed, temperature and humidity. These averaged variables are related to the flux through transfer coefficients. This same approach is commonly used to parameterize the surface fluxes in forecast models from variables resolved by the model. For example, based on the dimensional arguments, the exchange of sensible and latent heat at the ocean surface is expected to go as the wind speed time the air-sea temperature and humidity differences, respectively:

$$Q_H \cong -\rho_a c_p C_H U_r \Delta\Theta \tag{3}$$

$$Q_E \cong -\rho_a L_v C_E U_r \Delta Q \tag{4}$$

where $C_H$ and $C_E$ are the transfer coefficients for heat and mass known as the Stanton and Dalton numbers, respectively; $U_r$ is the wind speed relative to water (i.e., the wind speed-current difference); and $\Delta\Theta$ and $\Delta Q$ are the mean air-sea potential temperature and specific humidity. The uncertainty in the transfer coefficients for heat and mass remains one of the main obstacles to accurate numerical forecasts. Improvement of these transfer coefficients is a primary objective of this research.

## WORK COMPLETED

***Experimental Preparation:*** In preparation for the field work in the fall of 2011, the PI combined heat flux estimates from a number of recent field programs to look at the behavior of the transfer coefficients from prior experiments. These field programs including the ONR sponsored CBLAST program (Edson et al. 2007) and the NSF sponsored CLIMODE (Marshall et al. 2009) and GASEX programs. The CBLAST-LOW experiments were primarily conducted in low to moderate winds while the CLIMODE and GASEX experiments focused on air-sea interactions at moderate to high winds. The combined data set therefore covers a wide range of wind and stability conditions. For example, near surface winds of 15 m/s were commonly encountered over the North Atlantic during CLIMODE and the data set includes wind events with speeds over 25 m/s. These high wind events drive surface stresses that routinely exceed 1.0 $N/m^2$ and combined latent and sensible heat fluxes from the ocean into the atmosphere that exceed 1200 $W/m^2$. These enormous heat fluxes are driven by high winds and large air-sea temperature and humidity differences encountered over the Gulf Stream during cold air outbreaks. The CBLAST-LOW program collected 3 months of data from an Air-Sea Interaction Tower (ASIT) under low to moderate wind conditions. To data, the CBLAST investigations have focused on the role of swell on momentum exchange under low wind conditions while the CLIMODE investigations have focused on momentum exchange at high winds. This investigation focuses on heat exchange from low to high winds using the combined data sets. Preliminary results from this investigation were reported at the AMS 17$^{th}$ Conference on Air-Sea Interaction in Annapolis, MD.

***Main Experiment:*** The PI (Edson) deployed a turbulent and radiative flux package and associated mean meteorological sensors aboard the research vessel the R/V Revelle during the DYNAMO field program. In situ meteorology and high-rate flux sensors operated continuously while in the sampling period for DYNAMO Leg 3. This included all sensors operating during Leg 2 with the addition of a closed-path LI-7200 IRGA to the flux systems. Sea surface temperatures were measured by the group using the sea-snake floating thermistor and radiometric estimates of skin temperature in collaboration with Chris Zappa (LDEO/Columbia). NOAA/PSD operated a suite of remote sensing instruments for low clouds and light precipitation: the NOAA W-band cloud radar, a microwave radiometer, and a laser ceilometer. Aircraft overflights were made on November 13, 22 and 26 with all systems operational and good relative winds for our flux measurement systems.

Overall, these packages ran continuously in international waters from 4 September (start of Leg 1) to 31 December, 2011 (end of leg 4). The data return rate was nearly 100%. The data has been quality controlled and calibrated to produce means and bulk fluxes using the COARE 3.5 algorithm (Edson et al., JPO, 43, 1589-1610, 2013). These data are available through an anonymous ftp site maintained at UConn: ftp://dynamo.dms.uconn.edu/. These data include radiative and heat fluxes; surface stress; wave data; surface and near surface sea temperatures, salinity and currents; and other key variables specifically requested by DYNAMO/LASP PIs. Preliminary results from the field campaign were reported at the AMS 18$^{th}$ Conference on Air-Sea Interaction in Boston, MA.

## RESULTS

***Preliminary Research:*** The observational highlight of Leg 3 was the capture of an almost complete MJO cycle in our time series measurements. After a brief period of convective activity upon arrival, the measurements were characteristic of the suppressed phase of the MJO. Strong solar heating of the ocean overwhelmed the convective cooling by the atmosphere, and ocean surface temperature increased by approximately 1°C between 11-17 November (Yeardays 315-321). As shown in Figure

3, winds remained light and variable during this period and little precipitation was observed. In Figure 3, the velocity data were taken from the sonic anemometers on the forward mast. Poor relative wind directions were removed and the data was interpolated through these periods. Surface currents were collected from the ship's ADCP after QC by the OSU mixing group. Air temperature was collected by two aspirated T/RH sensors on the bow. Poor relative wind directions were also removed from these data to reduce the heat island effect of the ship. Sea surface temperature was measured by the sea-snake and corrected for cool-skin effects. Precipitation (P) was provided by an optical rain gauge after calibration with 6 other rain gauges. Specific humidity was calculated by combining these sensors with pressure measurements. Evaporation (E) was computed using the latent heat flux estimated by the COARE 3.5 algorithm. Accumulated totals of P and E are shown. The blue shaded area is therefore their difference.

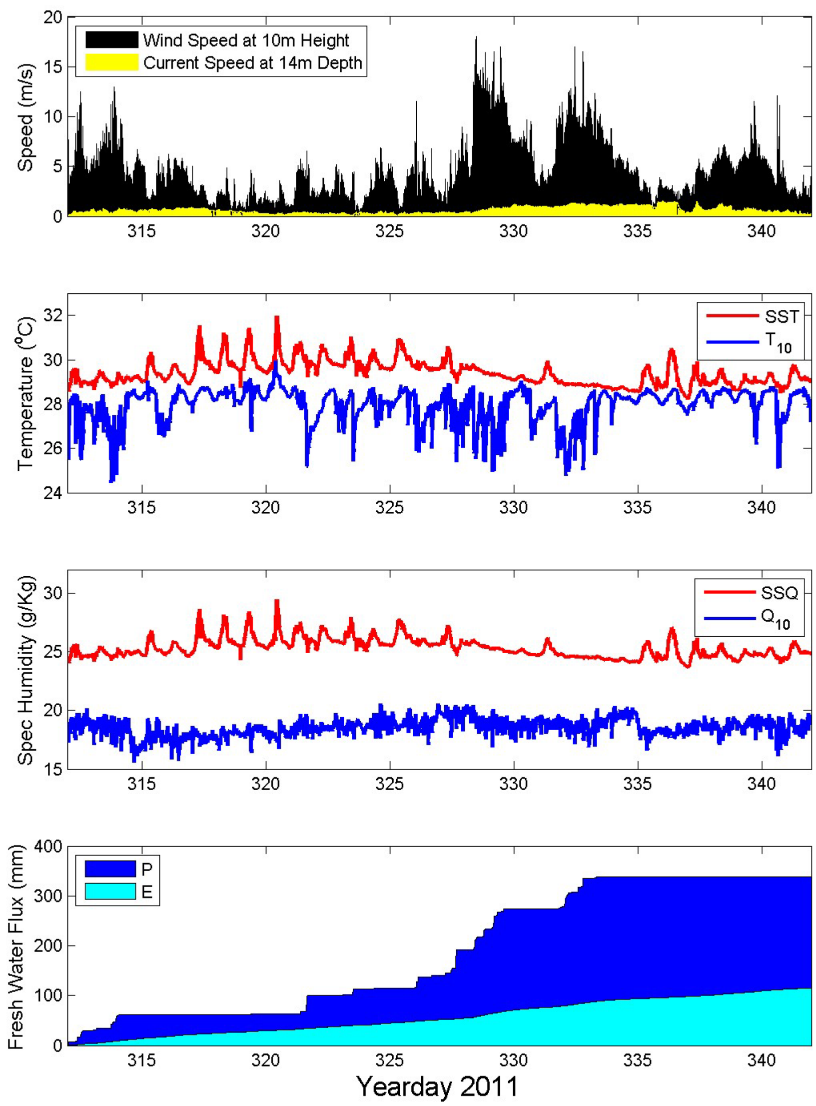


***Figure 1. Time series of mean meteorological and ocean surface variable during Leg 3.***

Atmospheric convection began to increase on 17 November (Yearday 321) with precipitation falling overnight. Wind speeds and convection gradually increased during the period between 18-23 November (Yeardays 322-327). Sea surface temperatures leveled off during this period due to a

gradual reduction in solar radiation and continued latent heat loss of approximately 100 $Wm^{-2}$. The active phase of the MJO was in full swing with the arrival of cyclone aided westerly wind burst on 24 November (Yearday 328). Ten-minute averaged wind speeds in excess of 19 m/s where observed over growing seas with significant wave heights of approximately 3 m. The sea-surface temperature dropped significantly during this period with combined sensible and latent heat loss to the atmosphere of approximately 200-400 $Wm^{-2}$. Moderate winds, precipitating convection and surface cooling continued through the end of November (Yearday 334). Overall, precipitation exceeded evaporation during this period. Although westerly surface winds around 5 $ms^{-1}$ continued into December, a drying out of the atmosphere aloft and associated reduction in convective activity was observed as the active phase of the MJO-related convection moved towards the maritime continent.

The flux group has begun to process the turbulence instrumentation on the forward mast to compute fluxes using the direct covariance (eddy correlation) method after correction for ship motion. Preliminary results from our analysis are encouraging. For example, Figure 2 shows a time series of surface stress and latent heat flux estimated from the direct covariance method and COARE 3.5 bulk algorithm during the westerly wind burst. In this figure, the solid background color represents the bulk estimates, while the solid line represents the DC measurements. The DC measurements are limited to more favorable relative wind directions to result the impact of flow distortion on our measurement. Nonetheless, the agreement between the two stress estimates is very good.

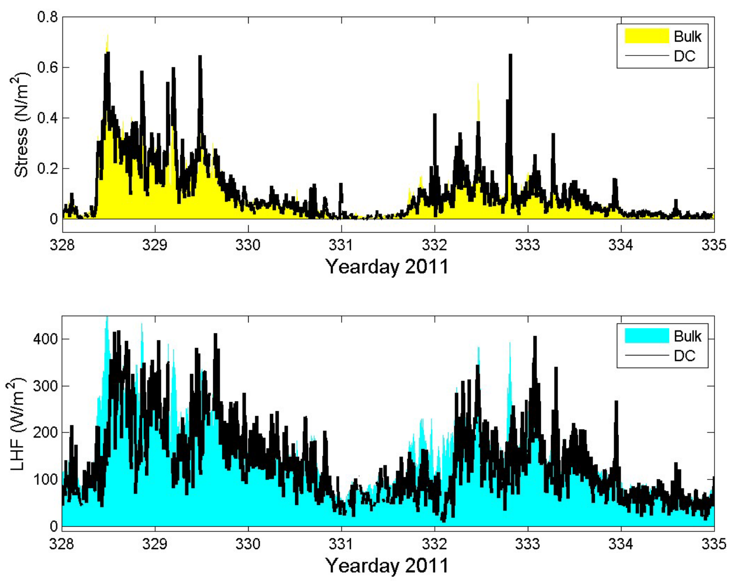


***Figure 2. Time series of surface stress (top) and latent heat flux (bottom) derived from the direct covariance and bulk aerodynamic methods. The solid color is the bulk and the black line is the direct measurements.***

**Surface Flux Parameterization:** A primary goal of our research is to improve the surface flux parameterization for latent and sensible heat used in these models and observational process studies. The starting point of this investigation is the comparison of the directly measured Stanton and Dalton numbers, i.e., found using (3) and (4) using the appropriate fluxes and means, with the COARE 3.5 algorithm (Edson et al. 2013). In COARE 3.5 the coefficients of sensible heat and moisture are assumed to be the same, suggesting similarity in the transfer of heat and mass. The investigation will

test the assumption of similarity and the consistency of these results with previous estimates of the Stanton and Dalton numbers from the CBLAST, CLIMODE and GASEX programs.

An example of this effort is shown in Figure 3 where the transfer coefficients computed from DC latent heat and buoyancy fluxes during DYNAMO and CLIMODE are compared. The four estimates of the transfer coefficients are in very good agreement. All four estimate exhibit the same overall characteristics of a minimum around 3-4 m/s that increases to a maximum in the transfer around 12 m/s before again falling off at higher winds. The ultimate goal of this research is the development of the COARE 4.0 algorithm and a qualitatively determined parameterization that captures these characteristics is drawn on this figure. A rigorous evaluation of this function is being conducted using these results combined with those from CBLAST and GASEX.

**Surface Fluxes:** The improved flux estimates are being used to investigate boundary layer response to air-sea interaction. For example, the exchange of heat across the air-sea boundary layers plays an important role in the thermodynamics of the coupled ocean-atmospheric system in the tropics. Of particular interest is the relative magnitude of the net shortwave (solar) radiative flux that heat the upper ocean versus the latent heat flux that cools it and drives atmospheric convection.

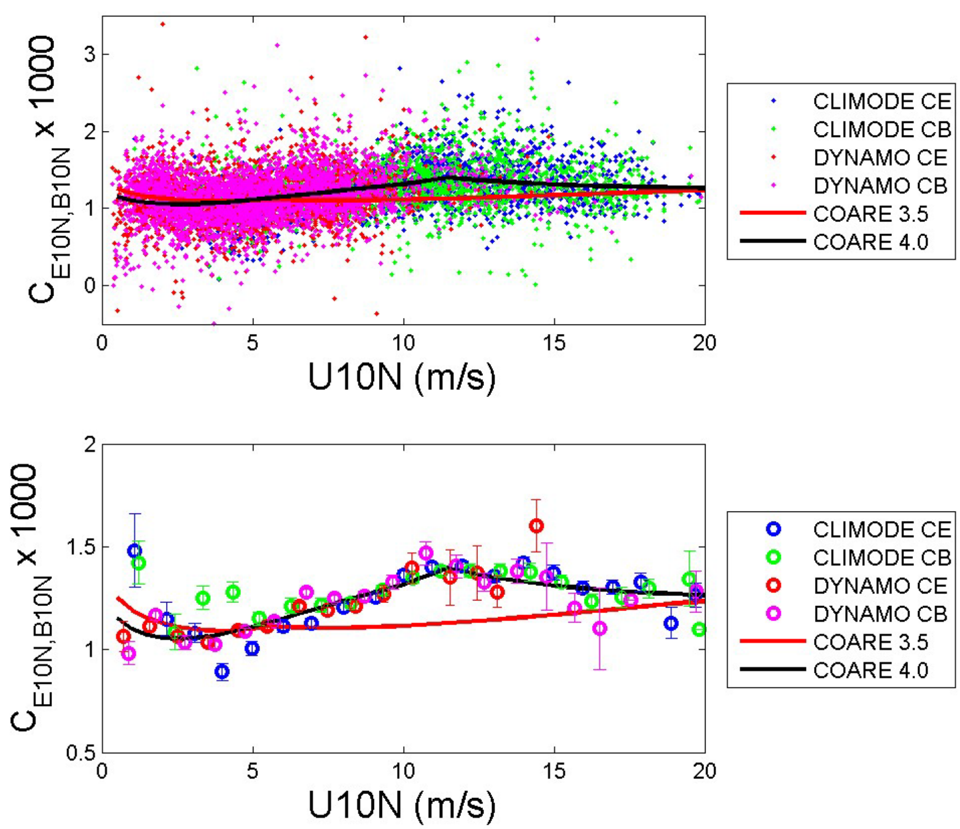


***Figure 3. Transfer coefficients for moisture and buoyancy computed from DC fluxes and their associated means. The two sets of transfer coefficients were generated from data collected during DYNAMO/LASP and the CLIMODE programs.***

A summary of the latent, sensible, radiative and net heat fluxes during Leg 3 are shown in Figure 4. The downward radiative fluxes were measured by the purgeometers (LW) and pyranometers (SW)

located on the top of the forward mast. The upward long-wave radiation was obtained using our SST measurements and corrected for IR reflection from downwelling long-wave. A commonly used parameterization of sea-surface albedo was used to estimate the reflected solar. The optimized set of mean meteorological and surface ocean measurements (temperature and currents) are used to compute the latent, sensible and rain fluxes with the COARE 3.5 algorithm. These measurements provide all of the terms in the surface heat budget

$$Q_{net} = Q_{SW} + Q_{LW} + Q_E + Q_H + Q_r \tag{5}$$

where $Q_{net}$, $Q_{SW}$, $Q_{LW}$ and $Q_r$ are the net heat, net solar, net IR, and rain-induced fluxes, respectively. The net heat flux is plotted in the 3rd panel and shows clear phasing with the active and inactive phases of the MJO with a release of energy during the active phase and oceanic storage of energy between events.

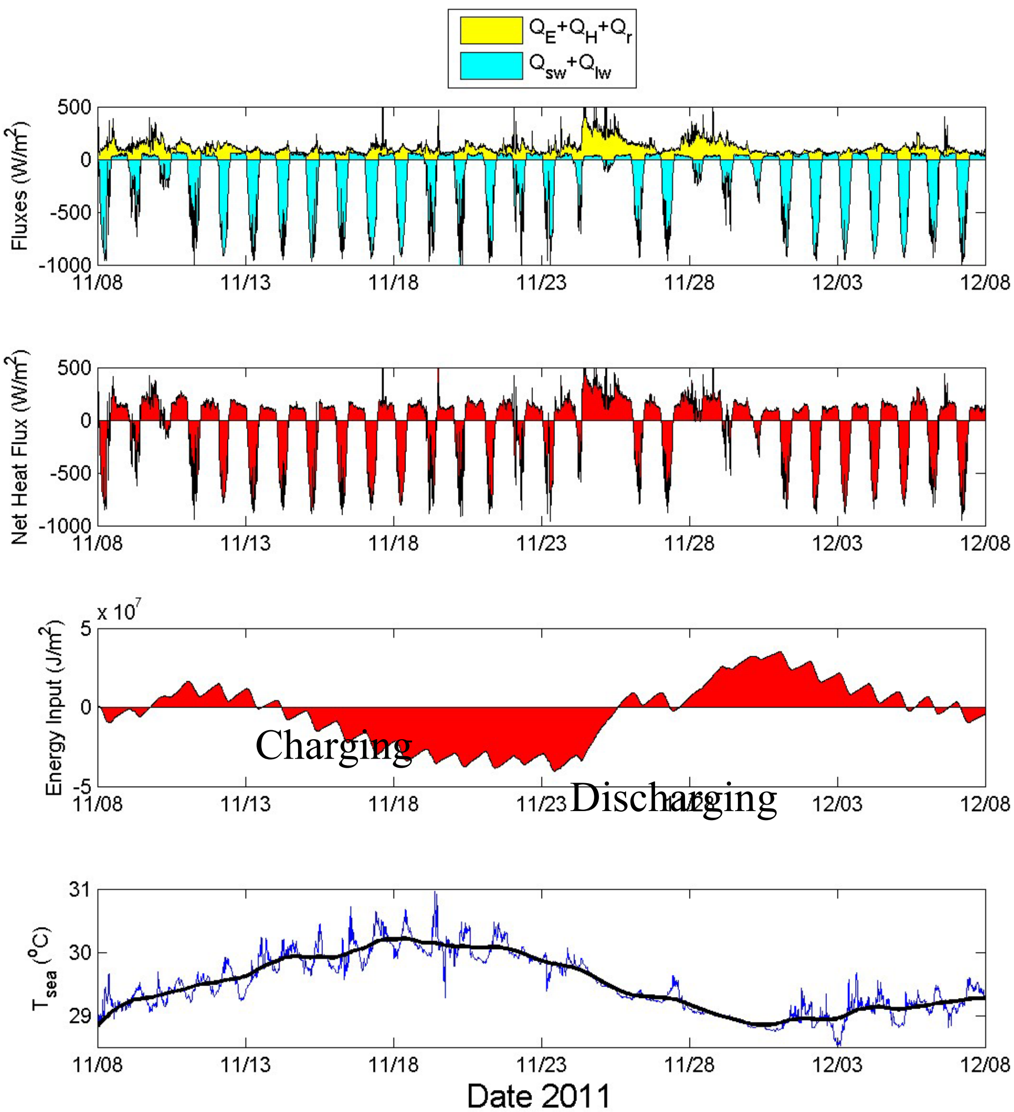


***Figure 4. (top panel) Heat and radiative fluxes during Leg 3, (middle panels) Qnet and its integrated value after a 20% reduction of the solar radiation to account for the fraction that penetrates through the mixed layer, and (bottom panel) the sea temperature at 5-m depth.***

It is important to note, however, that not all of this energy goes into heating of the mixed layer as a significant fraction of the solar radiation penetrates through this layer. Oceanic turbulence also removes some of the heat through the base of the mixed layer. The actual values of the penetrating solar and heat exchange at the base of the mixed layer are being calculated by colleagues at OSU. However, a reasonable estimate of the energy stored and released in the oceanic mixed layer can be computed by assuming that 20% of the solar radiation penetrates through the mixed layer. The energy flux is then determined by integration of the net heat flux over time after reduction of the solar radiation as shown by the bottom panel of Fig. 4. Plotted this way, the energy flux shows clear phasing of the energy input with energy stored during the suppressed phase and released during the active phase. As such, one can think of the ocean as a capacitor for the MJO, where the capacitor is charged when there is a net heat flux into the ocean. At least some of this energy is then released to the atmosphere during the active phase of the MJO under high winds and large latent heat exchange.

The large amount of heat supplied to the ocean during the suppressed phase of the MJO is clearly seen in the measurements between 14-22 November (Yeardays 318 and 326). This plot also shows a leveling off of the heating around 23 November (Yearday 327), which corresponds to the start of the active phase. The westerly wind burst is clearly associated with the active phase, and drove the net heat loss evident between 24 November and 1 December (Yeardays 328 and 335) and associated cooling of the ocean. The end of the time series again shows the heat supplied to the ocean (i.e., recharging of the capacitor) during the start of a new suppressed phase. Similar results were seen during MJO event captured during Leg 2.

The oceanic capacitor stores a significant amount of energy that may initiate (in tandem with favorable atmospheric condition, e.g., surface convergence and divergence aloft) and drive convection during the active phase of the MJO. Therefore, these observations supports the hypothesis: **The initialization and strength of MJO convection in the Indian Ocean is partially governed by the oceanic storage of energy during the suppressed phase and release of this energy during the active phase**, which has been addressed in several modeling studies. It true, one might expect that the strength of an MJO event would be affected by prior MJOs, i.e., a strong MJO is more likely to be followed by a weak MJO. We plan to test this hypothesis through analysis of the atmospheric and oceanographic data from the ship and mooring arrays.

**Ongoing Work:** The role that the ocean and air-sea exchange plays in driving the amplitude and phase of the MJO will be a focus of our collaborative investigation with the Ocean Mixing, Sounding and Remote Sensing groups. For example, the sea temperature appears to be out of phase with the surface heating in Figure 5, i.e., the SST (upper panel) is decreasing prior to the reversal of the net heat exchange out of the ocean. The physical processes responsible for this decrease are being explored with our collaborators at OSU and NOAA/PSD. Additionally, the strong wind events associated with the active phase of the MJO drive oceanic response that include rapid enhancement of the equatorial jet and deepening of the mixed layer. These processes are described in an overview paper that was recently published in BAMS (Moum et al., 2014) and a modeling/observation study describing the MJO disturbance captured during Leg 3 (Chen et al., 2014, in revision).

This past year's research investigated theories that appeal to the tropical atmosphere's interaction with the ocean to explain the Madden-Julian Oscillation (MJO) using DYNAMO and TOGA-COARE observations and reanalysis-based surface flux products. This work was conducted in close collaboration with Dr. Simon DeSzoeke of OSU. The investigation found that intraseasonal atmospheric deep convection within 15° latitude of the equator is in phase with increased surface wind

stress, decreased solar heating, and increased surface latent heat flux from the ocean to the atmosphere. Comparisons between the DYNAMO and TOGA-COARE data sets showed that the timing of convection, ocean surface flux, and SST is consistent from the central Indian Ocean (70°E) to the Western Pacific Ocean (160°E).

An important finding is that the mean surface evaporation observed in TOGA COARE and DYNAMO accounts for approximately half of the moisture convergence necessary to explain the mean precipitation (Figure 5). The observations show that the precipitation maxima in the active phase of the MJO are up to an order of magnitude larger than the relatively constant evaporation. Therefore, the main contributor of moisture for the rain events is moisture convergence in the convectively active phase of the MJO. The observed relations between surface evaporation and precipitation have implications for the mechanisms of moisture recharge and discharge in the MJO. These relations and air-sea exchange during DYNANO and TOGA-COARE are discussed in detail by DeSzoeke et al. (2014, in revision).

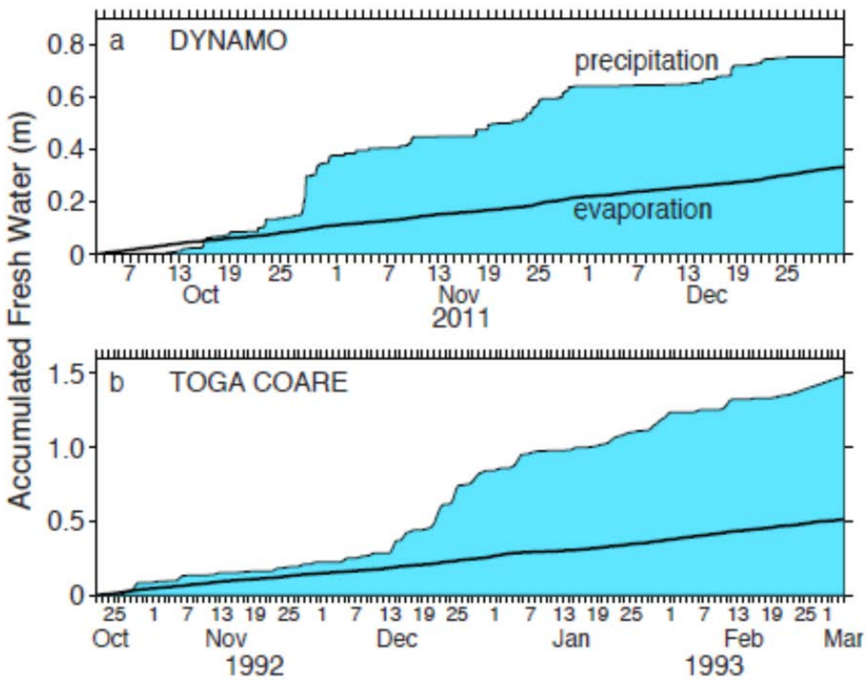


***Figure 5. Accumulated precipitation derived from the R/V Revelle and TAO/RAMA buoys for DYNAMO (a) and the IMET buoy for TOGA-COARE (b).***

## IMPACT/APPLICATIONS

None to date

## TRANSITIONS

None to date

## RELATED PROJECTS

The ONR portion of this program will work closely with investigators from the NSF/NOAA funded DYNAMO program. The results will also be compared with findings from the NASA/SPURS program.

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